



# Safe Operations of Unmanned Systems for Reconnaissance in Complex Environments Army Technology Objective (SOURCE ATO)

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## ABSTRACT

This paper examines the systems, hardware, and software engineering efforts required to overcome the challenges of operating autonomously around dynamic objects in complex environments. To detect these dynamic objects, the SOURCE ATO will utilize ARL/GDRS developed moving obstacle detection algorithms that will run on the Autonomous Navigation System (ANS) hardware.<sup>1</sup> These algorithms use data from multiple sensors including laser detection and ranging (LADAR), Electro-optic, and Millimeter-Wave Radar (MMWR) to produce detections. This limits erroneous identifications that occur when using only one sensor. This paper describes co-development of Safe Operation Technologies between the SOURCE ATO and the ANS development program. This approach allows a more rapid development cycle, which will enable both current and future ground combat vehicle systems the flexibility to readily adopt emerging software, process hardware, and sensor technologies.

## KEYWORDS

Autonomous Navigation System

SOURCE ATO

Unmanned Ground Vehicles

Navigation Sensors

Obstacle Avoidance

Autonomous Operations

## 1.0 Introduction

Operating autonomously around dynamic objects is a difficult aspect of land-based autonomous navigation. These dynamic objects include other vehicles, animals, and humans, with detection of human pedestrians being the most critically important. Humans present a particularly difficult detection challenge due to the diversity of sizes and postures they can present in a scene. Occlusions such as buildings or foliage, either for intentional camouflage or otherwise, complicate this challenge.

To detect these dynamic objects and address the challenges they pose to autonomous navigation, engineers at TARDEC, GDRS, and the Army Research Lab (ARL) are co-developing Safe Operations Technologies. The SOURCE ATO is utilizing moving obstacle detection algorithms developed by ARL/GDRS to run on Autonomous Navigation System (ANS) hardware. These algorithms use data from multiple sensors including LADAR, electro-optic, and MMWR to produce detections. The multi-sensor approach limits erroneous identifications that occur when using only one sensor.

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<sup>1</sup> The ANS is being developed by GDRS for the U.S. Army's Brigade Combat Team Modernization (BCTM) program.

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This co-development approach allows a more rapid development cycle, which will enable both current and future ground combat vehicle systems the flexibility to readily adopt emerging software, process hardware, and sensor technologies.

## **2.0 Requirements for using the ANS for the SOURCE program**

### **2.1 Sensors**

The ANS used on the SOURCE program requires several sensors, which must operate in a wide range of conditions. These sensors are responsible for detecting various types of obstacles in the external environment. Data from these sensors is used to aid detection of various types of terrain obstacles and man-made obstacles (e.g., walls, railing, mailboxes). It is used for detection, classification, and avoidance when needed, as well as reporting of any humans and vehicles that it observes. The autonomous system uses redundant sensing for fault tolerance, and includes the capability to operate in a purely passive sensing mode. The capability for both active and passive sensing provides opportunities for sensor fusion, which reduces false alarm rates and adds robustness when operating in adverse conditions. Since the SOURCE system must operate at high speeds when on roads, the sight ranges required for obstacle and collision avoidance at these speeds are the primary basis of sensor range and detection performance requirements.

### **2.2 Processing hardware**

The ANS used for the SOURCE program requires a state-of-the-art processing capability, which is divided into multiple line replaceable units (LRUs) for field servicing. The computing system is required to host several computing LRUs that will provide capability to continue the mission in a degraded mode in the event of an LRU failure. Redundant network switching and power supplies are also required. The autonomous system used for SOURCE must maintain an unused processing performance margin of 30% when operating.

### **2.3 Vehicle independent**

The ANS is a vehicle independent system and must be operable on a vehicle configuration which may not be known at the time the software is compiled, though allowing for reasonable limits in terms of typical ground vehicles and their missions. Therefore, the autonomous system must adapt its planning to vehicle size, shape, wheelbase, wheel and axle configuration, the specific obstacle-crossing capabilities of the vehicle, as well as its acceleration, deceleration, rough terrain handling properties, and steering capabilities.

## **3.0 General SOURCE architecture approach**

To meet these requirements and overcome the challenges being addressed by the SOURCE ATO, it is essential that the ANS design be scalable, flexible, efficient, and powerful. The system needs to be scalable because it must adapt to multiple configurations that may have different mixes of sensors and processing hardware on-board. The system needs to be flexible due to requirements to operate on a wide variety of vehicles with different capabilities, in a wide range of environments, and to adapt to changing environments, reduced vehicle capabilities, or varying sensing quality. The system needs to be efficient because the vehicle design is impacted by needs for large amounts of power, cooling, and computing hardware. Despite the efficiencies achieved within the design, the system still needs to be computationally powerful because of its autonomous mission requirements: optimizing vehicle behavior in a complex external environment such as operating among independently moving obstacles is inherently costly. The computational cost is even higher when the system must maintain low decision latency times and use data from multiple redundant sensor processing chains. The autonomous system design has produced a solution, based on commercial off-the-shelf (COTS) processing technology, that fully meets the challenge.

The scalability of the ANS is a consequence of making each sensing modality capable of performing reasonable perception tasks while allowing a wider variation in platform sensors and exploiting redundant sensing for a



performance gain. This scalability comes at the expense of additional processing logic in each sensor chain, as well as the logic needed to combine or fuse results from multiple sensor chains.

The autonomous system design achieves flexibility by exploiting redundant sensing modalities where possible, and by a decision-making process that determines a near-optimal allocation of resources that allows best possible safe speeds while preserving required levels of safety in the current environment. The price of this flexibility is the additional processing and reasoning required for the ANS to monitor its own health, the condition and performance of its sensors, and the mobility limits of the surrounding terrain so that it can maintain effective safety monitoring with available sensor data quality, or activate cleaning when degradation occurs due to window obscuration. Further flexibility stems from the compact and rugged nature of the autonomous system design, which expects tough use but requires a minimum of weight and volume, to allow its use on many platforms.

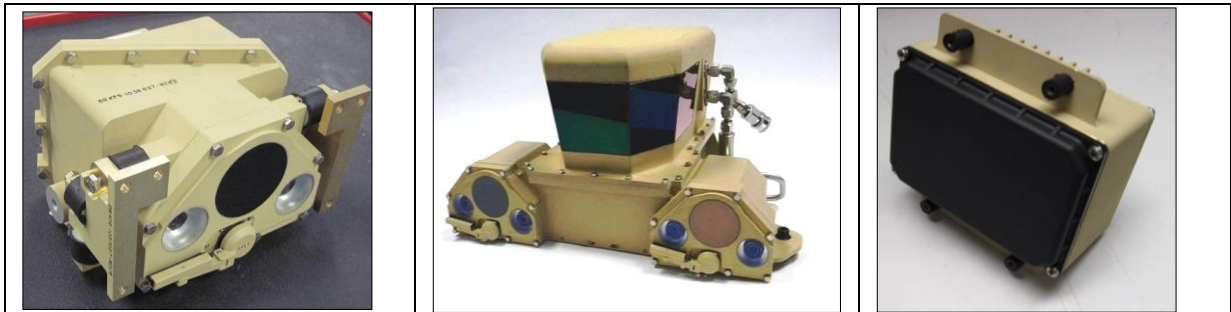
The autonomous system design achieves efficiency because during design any redundant computing is eliminated by modularizing the computing steps, using computed outputs for multiple purposes, and eliminating duplication where possible. Our sensor and processing allocation process ensures that the autonomous system achieves the near-maximum safe predicted performance. It does so based on the resources that are available at the time, and in the case of sensors, the quality of the sensor data under the current conditions. The system's hardware is efficient because it facilitates the tree-like convergence of the large quantities of sensor data coming from many sensors into several subsidiary computing LRUs that further reduce the raw data into more directly meaningful attributes of the environment, then into a master computing LRU that combines attribute data with previously stored information and uses reasoning techniques to develop the commanded behaviors and outputs.

The system achieves the required computational power in several ways. It exploits recent COTS innovations in multi-core low-wattage processors for general processing. It adopts COTS massive parallel processing capabilities to achieve higher performance-to-cost and performance-to-power consumption ratios. Additionally, it uses COTS programmable hardware for many low-level streaming mathematical computations at a fraction of the power and space required to perform these computations on CPU hardware. The cost of moving data is reduced by streaming from the field programmable gate arrays (FPGAs) directly into DRAM memory and by exploiting high speed COTS network innovations. This power is then multiplied by providing multiple computational LRUs and a significant computational design margin.

### **3.1 Top level ANS design**

#### **3.1.1 Sensors for the SOURCE ANS**

The autonomous system sensors come in two major packages: an imaging module and a LADAR module. The imaging module, shown in Figure 1a, includes High Definition (HD) visible light cameras with High Dynamic Range (HDR) capability and a very wide horizontal field of view (FOV), as well as a long-wave infra-red (LWIR) imaging sensor. The LADAR module includes the capabilities of two imaging modules in a stereo configuration and also adds a LADAR, as shown in Figure 1b. Stereo processing is performed in hardware for speed. Each LADAR has a wide and fast rotary azimuth scan to forward, an adjustable optical elevation scanning pattern with respect to horizontal, and provides the system with up to a quarter million range returns captured from surfaces beyond 100 meters during each azimuth scan period. Two other sensors make up additional modules: the MMWR shown in Figure 1c, and the Global Positioning System/Inertial Navigation System (GPS/INS) (not shown). The MMWR is capable of detecting humans and vehicles at medium ranges over a wide forward arc, and can detect vehicles as far out as 200 meters within a smaller forward arc. The hardened GPS/INS provides high-quality inertial and filtered navigation data.



**Figure 1. Autonomous Sensors.** From left to right, **Figure 1a** shows a SOURCE autonomous system imaging module with 3 camera apertures and wiper. **Figure 1b** shows a SOURCE autonomous system LADAR module with 2 imaging modules in stereo configuration and a high performance LADAR. **Figure 1c** shows an earlier but similar version of the COTS MMWR with custom back housing.

Since this autonomous system operates on a vehicle expected to be used off-road, the ability to clean the sensors is essential. This is provided by wipers and sprayers. During autonomous operation, the autonomous system is required to clean the sensors when needed and adapt to changes in lighting, weather, and surface conditions without operator intervention. Finally, the sensors must also provide sensing data for a human operator at any time if requested. Since the operator's display cannot typically show the extreme dynamic range of an outdoor scene, the autonomous system reduces the displayed dynamic range while preserving scene detail, and compresses several streams of video data with low latency and high efficiency using hardware-based H.264 encoding to preserve communications bandwidth.

The overall sensor design is very modular and flexible. The consideration of cleaning issues and determining sensor performance regularly in the local environment greatly enhances adaptability. The design parameters discussed above provide an autonomous system sensor suite with very robust overall performance and allow the vehicle equipped with the ANS system to appropriately maximize its performance.

### 3.1.2 Computing for SOURCE autonomy

The ANS computing system is a liquid-cooled chassis, as shown in Figure 2. It contains several computational LRUs that are interchangeable, as well as a failover power supply LRU and a high speed, redundant switching LRU. Each of the computational LRUs is roughly similar in architecture to a high-end laptop and contains a multi-core general purpose processor with cache and DRAM main memory, a highly parallel processing engine, and dedicated hardware level processing and sensor interfaces through the use of high capacity FPGAs. The LRUs communicate with each other and with the sensors via high speed switched connections. The computing system is self-configuring. With the autonomous system software hosted, in the event of a failure the system is able to stop safely, reconfigure itself into a new processing arrangement, and continue the mission. The design has been optimized to provide a balance of flexibility and adaptability with a design that incorporates efficiency measures while providing state-of-the-art computing power for the mission.



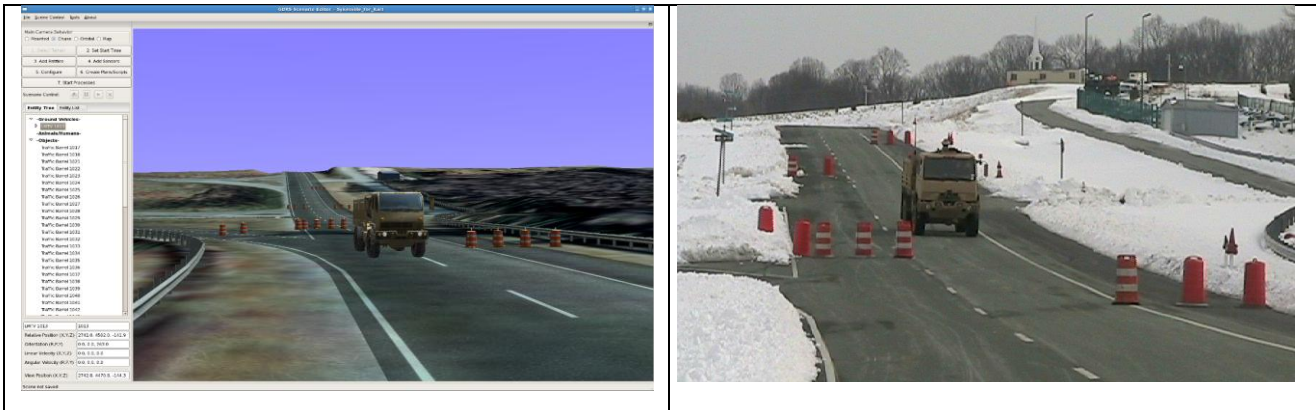
**Figure 2.** Hardware utilized for the SOURCE autonomous computational system.





### 3.1.3 Simulation, implementation, and testing of SOURCE

A detailed real-time simulation has been developed for the SOURCE ANS system. This simulation provides specialized software to generate real-time simulated LADAR, stereo disparity, and both visible and Infra-Red (IR) image data based on the simulated world. While running in this simulation, the SOURCE autonomous system software gets all perception data and dynamic feedback from the simulated world itself, allowing “full immersion” testing of the software. Simulated and real SOURCE autonomous system scenarios are shown in Figures 3a and 3b for comparison.



**Figure 3. SOURCE Autonomous System Scenarios.** From left to right, **Figure 3a** shows a simulated obstacle avoidance execution on a local road system. **Figure 3b** shows an actual obstacle avoidance execution on a local road system at a location matching that shown in Figure 3a.

### 3.1.4 Example Platforms/Hosts

The ANS was developed from the start for installation on multiple vehicle types (see Figure 4 below). Upon initialization, the autonomous system receives a full set of vehicle configuration and sensor placement and alignment data that is stored on the platform itself. The software also receives factory-measured intrinsic calibration parameters from the sensors on the vehicle while the software initializes and configures the sensors. The autonomous system software is then knowledgeable enough to determine which terrain or other obstacles might interfere with the vehicle’s wheels or its overall envelope when driving a given trajectory. The system also adapts its planning as needed to the specific obstacle crossing capabilities of the vehicle. It also adjusts to the acceleration, deceleration, rough terrain handling properties, and steering capabilities of the vehicle. Since the algorithms for the autonomous system typically resolve the underlying terrain profile relative to the vehicle and process the sensor data into vehicle-relative coordinates, they can easily adapt to normal variations in sensor placement among vehicles.

Although different vehicles can have a completely different mix of sensors, the same SOURCE autonomous system software will still operate effectively within the limits of the sensor performance. For example, a high-performance platform might have LADAR modules front and rear, a GPS/INS, a MMWR, and two side-looking imager modules, while an Autonomous Platform Demonstrator (APD) configuration now used for SOURCE has a front-mounted LADAR module and three imager modules looking to the left, right, and rear. For a more limited capability, this autonomous system could be used with a non-redundant vehicle configuration by mounting only passive stereo imaging sensors, or only a LADAR, to further reduce platform cost. Because of this built-in flexibility, the autonomous system can also be adapted to emerging sensors without dramatic changes to the underlying architecture.



**Figure 4.** A few of the many platforms that the SOURCE autonomous system has been hosted on or run on. In some cases, an older pre-prototype version of the LADAR or imaging module is shown.

#### 4.0 Specific SOURCE approach

Figure 5, provided at the end of this paper, is a detailed SOURCE architecture diagram.

#### 4.1 SOURCE architecture

The primary sensor used for detection during the SOURCE testing is the ANS Engineering Development Unit (EDU) LADAR, housed in a LIPM enclosure. The ANS LIPM consists of an ANS-developed EDU LADAR and a pair of Image Perception Modules (IPM) located on either side of the LADAR. Each IPM consists of an infrared and color camera. The two IPMs mounted in the enclosure can operate in a stereo pair configuration. Although the SOURCE system architecture can accommodate three additional IPMs (left facing, light facing, and rear facing), only the forward LIPM is installed at this time. The LADAR and IPM data from the LIPM is sent over an Ethernet fiber connection to the MEBB Enclosure.

The navigation sensor is GPS/INS. It is connected to the Multiple Engineering Bread Board (MEBB) enclosure through an Ethernet link and PPS connection. Differential GPS for the system is obtained through DGPS.

Command and control communications for the SOURCE system are implemented primarily through a pair of radios, one located on the vehicle and one located at the ground control area. The radio located on the vehicle supports a 10/100 MBit Ethernet link to a 10 Gigabit Ethernet switch that is located in the MEBB computing enclosure. The SOURCE platform is set up to incorporate other radios as mission changes occur.

The MEBB computer system (ACS) is the processing center of the ANS. All sensor data is processed within the ACS and correlated to establish the digital representation of the environment surrounding the platform, thus enabling autonomous operation.



## 4.2 Sign detection and interpretation

Sign detection and interpretation is one of the perception-based functions included in Safe Operations Technology. Sign detection and interpretation uses color and low-light video imagery to detect, localize, and interpret traffic signs. The algorithm is based on Scale-Invariant Feature Transforms (SIFT). SIFT uses multi-scale image data to locate key points in the image. The SIFT technique has the advantages of being invariant to image scale and rotation, and partially invariant to change in view points and illumination. Local feature data is extracted around each key point and then used for matching against exemplar signs. For speed limit signs, character recognition processing is used to analyze the region of the image from the sign to determine the speed limit value. Once the sign is interpreted, the resulting location and sign type is output to Road Registration. Road Registration utilizes the Sign Detection and Interpretation results to adjust the Short Range Plan which is based on the rules of the road. Additionally, the sign information may be used to update the Apriori Road Data to also account for the result of the sign.

## 4.3 Accelerated testing

Close collaboration allows the SOURCE technology to be integrated efficiently with the ANS hardware and software architecture. This will reduce cost and risk associated with transferring ANS technology to the Brigade Combat Team Modernization (BCTM) Increment 1 follow on. Although the SOURCE-developed technology will not necessarily meet all BCTM process requirements, the focus is on resources for the technical challenges outlined in the SOURCE ATO Statement of Work. An extra transition phase within ANS will support BCTM process requirements before incorporating any SOURCE technology into the ANS SDD system.

The SOURCE program will provide ANS operational time by running the system on two different platforms in a number of test scenarios. One platform used is the T2, which is a small, responsive Jeep-based vehicle. The other is the APD, which is a highly mobile, skid steer vehicle. The test scenarios will be conducted in various Military Operations in Urban Terrain (MOUT) sites during planned engineering evaluation and test events outlined in the SOURCE master plan. These test hours on the ANS provide documented experience that will be useful in proving ANS maturity levels when certifying the system for Safety at test ranges.

In conclusion, the SOURCE program will accelerate content planned within the ANS program through SOURCE test events that test the software design and code in more frequent cycles than utilizing the ANS test schedule alone. This will result in more frequent scrutiny of the code by more experts before testing and additional performance analysis of the software after testing.

New capabilities that were not planned within the ANS program will be incorporated through the SOURCE program. This original SOURCE-developed content will leverage the existing ANS interfaces, architecture, and hardware capabilities as a basis for new efforts. These new efforts are sign detection and response behavior based on some signs, and detection and avoidance of small object obstacles, such as animals.

Finally, SOURCE adds maturity to content that has been developed within the ANS program through the added development cycles, test time, and performance analysis. Capabilities that will be further matured include General Dynamics Westminster (GDW) LADAR human detection, stereo human detection, stereo vehicle detection, dynamic obstacle avoidance, and planning an on-road network.

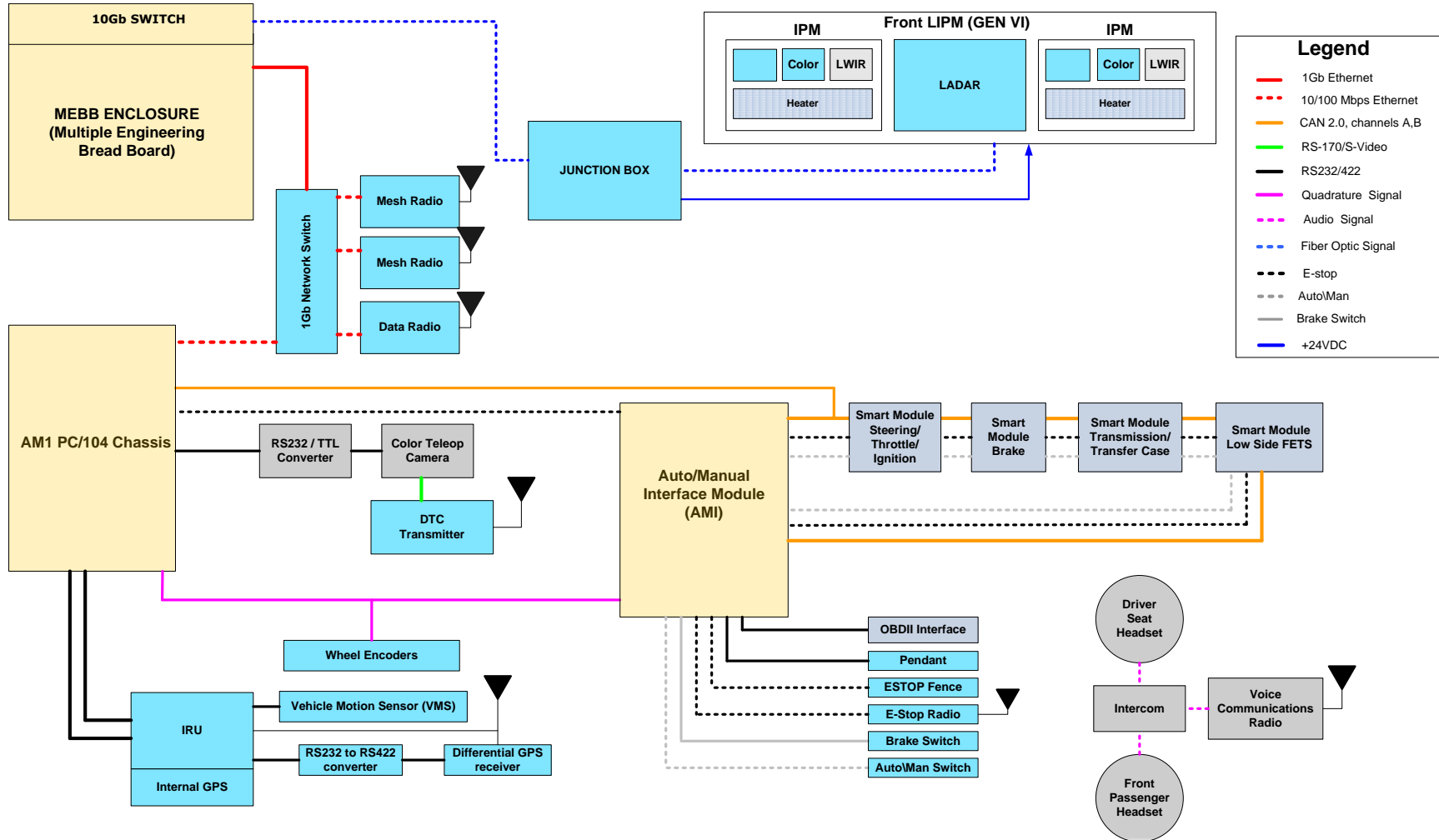
## 4.4 Disclaimer

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**Figure 5.** SOURCE Architecture Diagram.